Real-Time Optimized Earth Observation Autonomous Planning

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Abstract–**Earth monitoring systems of the future may include large numbers of inexpensive small satellites, tasked in a coordinated fashion to observe both long term and transient targets. For best performance, a tool that helps operators optimally assign targets to satellites will be required. We present initial results from algorithms developed for real-time optimized autonomous planning of large numbers of small single-sensor Earth observation satellites. The algorithms will reduce requirements on the human operators of such a system of satellites, ensure good utilization of system resources, and provide the capability to dynamically respond to temporal terrestrial phenomena. Our initial real-time system model consists of approximately 100 satellites and large number of points of interest on Earth (e.g., hurricanes, volcanoes, forest fires) with the objective to maximize the total science value of observations over time. Several options for calculating the science value of observations include the following: 1) total observation time, 2) number of observations, and the 3) quality (a function of e.g., sensor type, range, slant angle) of the observations. An integrated approach using integer programming, network optimization and astrodynamics is used to calculate optimized observation and sensor tasking plans.**

I. Introduction

> "...Thus far, we are only experimenting with long term weather, climate, and natural hazard prediction. The quest for a true predictive capability for Earth system changes requires a flexible and progressive space system architecture that is responsive to our needs based on our current understanding of the system as well as accommodating emerging needs in the coming decades. We need to design and establish a smart, autonomous and flexible constellation [of] Earth observing satellites which can be reconfigured based on the contemporary scientific problems at hand. Such a constellation would exploit a combination of active and passive sensing sensors in ways that we can perhaps imagine today....."

This is a quote from the remarks of former NASA Administrator Daniel S. Goldin "The Frontier of Possibilities" presented at the International Astronautical Federation on October 3, 2000. It clearly describes the underlying rationale for the multi-year project in which we are developing algorithms for resource allocation via autonomous reconfiguration of satellite webs consisting of heterogeneous Earth observation sensor platforms.

The development of these algorithms and a simulation testbed in which they reside, the Earth Phenomena Observing System (EPOS), will reduce requirements on the human operators of satellites, improve system resource utilization, and provide the capability to dynamically respond to temporal terrestrial phenomena. Examples of triggering events are localized transient phenomena that have a significant impact on human life such as volcanic eruptions, weather (hurricanes, tornadoes, etc.), algae plumes, large ocean vortices, ice shelf break-up, seismic activities, oil spills, magnetic anomalies, and search and rescue.

The current version of EPOS can perform real-time (re)planning and control, where "real-time" is taken to mean the capability to create a future plan while execution of a previously developed plan is taking place. In addition, the future plan is gracefully spliced into the executing plan without disrupting the system.

II. Future Operational Concept

In the year 2020, automated mission management will be required to help NASA achieve their Sensorweb vision. Draper's vision is to provide functionality for that mission manager, EPOS 2020. Key technology required for the full EPOS 2020 is being developed under our current 2 to 3 year effort.

In 2020, many Earth observing systems will be in place, each with its own ground facilities, communication and data protocols, satellite characteristics and observation schedules. There will be hundreds of Earth observing satellites and relatively few will be identical. In most systems, satellite maneuvering will be reserved for station-keeping only. From EPOS perspective these are "coasting satellites" – EPOS observation schedules must utilize the satellite's existing orbit. Some of the systems have satellites that can be dynamically tasked through in-plane maneuvering. For EPOS purposes these are referred to as "maneuvering satellites." These satellites will be easily upgraded and refueled using technology currently being developed [5]. We hypothesize there will be a coordinating ground station that has: 1) communication with these Earth observing systems, 2) a given set of data/information interchange protocols that provides the mechanism to exchange data with these varied systems, 3) visibility into whatever parameters are needed to model these systems, and 4) the capability to influence the observation schedules of these systems. This is illustrated in Figure 1. When a target becomes known, the coordinating ground station calculates which of the satellites controlled by the Earth observing systems can provide suitable information at the appropriate times and uses that knowledge to send appropriate *viewing requirements* to the individual system's ground stations. The individual ground stations look more closely at the availability and appropriateness of the satellites within its control, especially dealing with the priority of all requests for satellite assets. An inability to satisfy the *viewing requirements* is communicated back to the coordinating ground station.

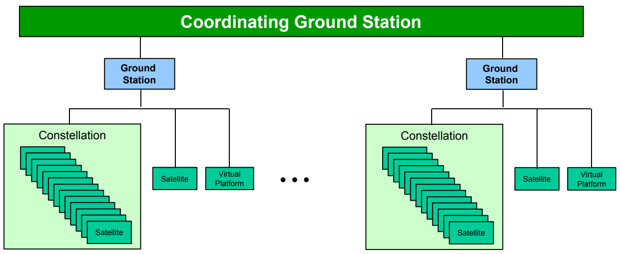

Figure 1: Year 2020 Operation Concept

This concept of operations includes planning and control of constellations and collaborative groups. Constellations are defined as a system employing two or more spacecraft whose orbits, operations, and observations are coordinated to provide global coverage or to improve temporal resolution from an altitude below GEO [4]. Constellations operate within constraints (e.g., keeping relative position in an orbital plane) that a planning and control system must recognize. Collaborative groups are temporary sets of satellites/virtual platforms that have commonality in their objectives; satellites can simultaneously belong to two collaborative groups. These groups "exist" (i.e., are formed) in the coordinating ground facility for the time period during which they are executing a plan. In our concept of operations, a satellite within a constellation can also be a member of a collaborative group as long as the constellation constraints are not violated.

III. APPROACH

The first steps in the development of EPOS have been taken over the last two years. This initial implementation of EPOS is based on Draper's autonomous system's planning framework [3], which is used to decompose the problem into tractable subproblems or levels. Each level is then solved using an approach that integrates astrodynamic modeling and combinatorial optimization.

A. PLANNING FRAMEWORK

The basic building block of Draper's real-time planning and control architecture for autonomous systems [3] is shown in Figure 2. It is an extension of the *sense-think-act* paradigm of intelligence, and is similar to the military's Observe-Orient-Decide-Act loop [2]. The key elements are modules for situation assessment, plan generation, plan implementation, and coordination.

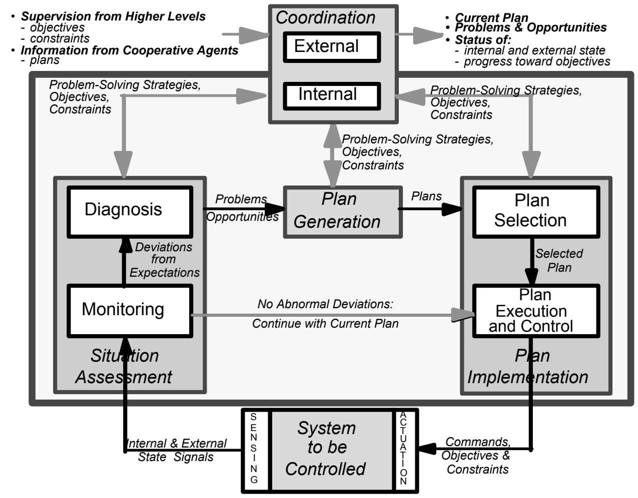

Figure 2: Planning and Control Architecture Modules

The planning and control problem addressed in our effort is complex enough to warrant hierarchically decomposing it in order to make it tractable. Replanning takes place at the lowest level possible, without disturbing other plans unless additional resources are needed. Hierarchical decomposition is appropriate for applications in which there is significant stochasticity. In such systems, it is not practical to make detailed plans too far into the future, since the state of the world (e.g., new targets of interest) and the state of the system (e.g., a satellite sensor fault) can change.

In order to make the optimization problem tractable, hierarchical decomposition is used both temporally and functionally. The decomposition is characterized by higher levels that create plans with the greatest temporal scope (longest planning horizon) but with the least detail. At lower levels, the planning horizon becomes shorter (nearer term), but the level of detail of planned activities increases. The less detailed plans at the higher levels coordinate or guide the generation of solutions generated at the lower levels. Indeed, planning actions over extended periods of time at a high level of detail is typically both futile and impractical. Futile because detailed actions planned on the basis of a specific prediction of the future may become obsolete well before they are to be executed due to an inability to accurately predict the future. Impractical because the computational resources required to develop detailed plans over extended periods of time may be prohibitive either in cost or availability or both. The relationship between the levels of the hierarchy and the planning horizon and level of plan detail is shown in Figure 3.

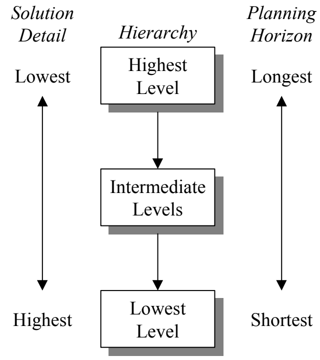

Figure 3: Temporal Decomposition

One way of grouping the types of decisions that need to be made for EPOS is shown in Figure 4. Three decision tiers are present: 1) System, the top tier focuses on decisions that impact the entire EPOS (e.g., which targets to collect data for); 2) Collaborative Group, the middle tier addresses issues that relate to a group of multiple satellites being used to collect data on a target (e.g., which satellites make up this group); and 3) Satellites, the lowest tier addresses decisions relevant to the individual satellites making up each collaborative group (e.g., what burns should be executed to achieve a certain level of required coverage). This decomposition is natural for satellite operations.

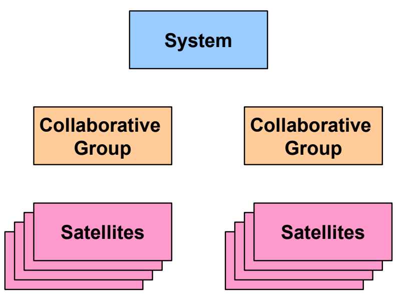

Figure 4: Three Tiered EPOS Hierarchy

Another decomposition, one based around seven key levels of decision-making is described in Figure 5. The longer term, EPOS-wide issues are determined at the upper levels, while shorter-term decisions are lower down in the list. This is a decision-centric approach to decomposition compared with the entity-centric approach of the three tiers. The planning and control architecture modules of Figure 2 can be applied within each of these decision levels. Note that the description of the decision levels shown in Figure 5 presents the capabilities of a complete EPOS system, including functionality that has not yet been implemented.

	Mission Manager Levels	Decisions
System Tier	System Level	Select locations on Earth for observation; for each location being observed: what are the candidate satellite platforms?
	Configuration Level	Which satellites need to be refueled? Which satellites need to be launched?
Collaborative Group Tier	Platform Assignment Level	Which satellites are to be actually used for observation?
	Observation Level	For each satellite, when and for what target should the sensors be used?
Satellite Tier	Maneuver Level	For each satellite, when and with what Dv should the maneuvers be made?
	Sensor Level	For each sensor, when and in which direction should it be pointed?
	Data and Communication Level	For each satellite, what data to store when, and what data to communicate when?

Figure 5: Decision Levels

The development of EPOS is an evolving process. Previous versions of EPOS [1] focused on an initial version of the observation level (which included a person-in-the-loop) and an autonomous implementation of the maneuver level. The current version of EPOS, 2.0, is focused on an autonomous implementation that provides the decisions at the platform assignment, observation and sensor levels. This implementation is being done using an integrated two-level optimization formulation.

The top optimization level is described in subsection C and the bottom optimization level is described in subsection D. The top level creates the initial platform and observation plans, the bottom level takes those as inputs and creates the final platform, observation and sensor plans in the form of sensor pointing command over time.

The optimization algorithms employed by each of those levels rely on data that must be derived through astrodynamic modeling. That modeling is described in the next subsection.

B. Astrodynamics

Observation planning algorithms require knowledge of the evolution of target illumination and of sensor-to-target relative position. Dynamic models are used to answer the following essential questions for each time t in the planning interval:

- Which targets are in sunlight?
- Which satellites can potentially view a given target, in the sense that the line of sight from satellite to target is not obstructed?
- How must the sensor on such a satellite be oriented to have the target at the center of its field of view?
- Paying attention to pointing angle limits, can the sensor be oriented so that the target is somewhere in its field of view?

Write $r(t)$ for the earth-centered inertial (ECI) coordinates of an earthbound target at time t, and $v(t)$ for a unit vector normal to the earth's surface (local vertical) at $r(t)$. Both $r(t)$ and $v(t)$

are determined from target geodetic latitude, longitude, and time, using an analytic representation for the right ascension of Greenwich.

To determine if the target is in sunlight at time *t*, we need ECI coordinates *u(t)* for the direction to the sun. An analytic representation is used. The target is in sunlight when the dot product $v(t) \cdot u(t)$ is positive.

Satellite orbital motion is modeled using the simple J_2 secular theory, but the software could be easily modified to use a more sophisticated orbit propagator. ECI position coordinates, *s(t),* for a satellite are computed from its orbit elements using standard two-body mechanics formulas.

The look direction, from satellite with coordinates *s(t)* to target with coordinates *r(t),* is computed as follows:

$$L_{rs}(t) = \frac{r(t) - s(t)}{\left\| r(t) - s(t) \right\|}$$

The satellite can potentially view the target, in the sense that the line of sight is not obstructed by the earth, if the following dot product condition holds:

$$v(t) \cdot L_{rs}(t) < 0$$

Satellite attitude must be modeled in order to answer questions about sensor orientation. Let $A_s(t)$ denote the nominal attitude of the satellite with coordinates *s(t)* at time *t*. The development version of our system assumes sun-nadir steering for each satellite; one spacecraft axis points to nadir and a second axis is normal to the plane spanned by nadir and the sun direction. An operational planning tool would support considerably more flexible specification of satellite attitude profiles.

Attitude $A_s(t)$ is understood to be a coordinate transformation from ECI frame to nominal spacecraft body frame. Sensor orientation is specified as a second coordinate transformation, $\tilde{A}_s(t)$, from nominal spacecraft body frame to a frame fixed in the sensor. The composite transformation, $\tilde{A}_s(t)A_s(t)$, could be realized in either of two ways:

- Steer the spacecraft so that $A_s(t)$ is the transformation from ECI to actual spacecraft body frame. Gimbal the sensor so that $\tilde{A}_s(t)$ is the transformation from spacecraft body frame to sensor frame.
- Steer the spacecraft only, so that $\tilde{A}_s(t)A_s(t)$ is the transformation from ECI to the sensor frame.

In either case, we regard $A_s(t)$ as given and $\tilde{A}_s(t)$ as something to be chosen.

Let ℓ be a unit vector in the sensor look direction, expressed in the sensor frame. The target is at the center of the sensor field of view if the following condition holds:

$$\tilde{A}_s(t)A_s(t)L_{rs}(t) = \ell$$

This condition determines $\tilde{A}_s(t)$ up to rotation about ℓ. It determines the first two angles $x(t)$ and $y(t)$ in a suitable Euler angle sequence, in other words.

The target remains somewhere in the sensor field of view provided that these Euler angles are chosen from intervals $[x(t) - \Delta x, \quad x(t) + \Delta x]$ and $[y(t) - \Delta y, \quad y(t) + \Delta y]$, respectively. Here Δx and Δy are constants of the sensor (field of view half-widths).

Four additional parameters of the sensor, $x_{\min}$, $x_{\max}$, $y_{\min}$ and $y_{\max}$ are used to specify feasible intervals for the two Euler angles. For the sensor to be able to view the target at time *t*, it is necessary that the line of sight be unobstructed (dot product condition given earlier) and that the intervals I_x and I_y be nonempty, where

$$I_x = [x(t) - \Delta x, \quad x(t) + \Delta x] \cap [x_{\min}, \quad x_{\max}]$$
$$I_y = [y(t) - \Delta y, \quad y(t) + \Delta y] \cap [y_{\min}, \quad y_{\max}]$$

C. *TOP-LEVEL OPTIMIZATION*

The top level optimization's problem is to find the primary target for each sensor so that the *total science value at time t* (including extra for simultaneous viewing) is maximized provided that:

- no more than one of each type of sensor is tasked for each target[1]
- no more than two (different) sensors are assigned per target
- demand for data storage on a satellite does not exceed available capacity.

The problem is specified through static data that describes the available satellites and their associated ground stations and dynamic data that specifies that targets of interest, which targets can be viewed by a particular satellite and which ground stations can communicate with a satellite at a given time. In the discussion that follows, the terms satellite and sensor are often used interchangeably. The schedule is being done for each *sensor*. Conceptually, one can think of a satellite containing a single sensor. It is of no consequence to the formulation that follows if multiple sensors are contained on a single satellite. To begin the derivation of the problem, the following sets must be defined:

[1] This is a simple model to handle the assumed non-linearity of the value function, i.e., that the value from two observations by the same type sensor during any time period is less than twice the value of one observation.

N = number of satellites/sensors

M = number of targets

L = number of ground stations

S_{EO} = Set of sensors of type EO

S_{IR} = Set of sensors of type IR

S_{SAR} = Set of sensors of type SAR

Dynamic Inputs

The dynamic inputs to the top level optimization specify data that is changed from one pass to the next. The set of targets that a particular sensor can view at time t are specified as:

$$o_{ij}^t = \begin{cases} 1 \text{ if satellite/sensor } i \text{ can observe target } j \\ 0 \text{ otherwise} \end{cases}$$

The set of ground stations that a satellite can communicate with at time t are specified as

$$q_{ig}^t = \begin{cases} 1 \text{ if satellite/sensor } i \text{ can communicate with ground station } g \\ 0 \text{ otherwise} \end{cases}$$

The values of o_{ij}^t and q_{ij}^t are derived using the methods described in the subsection describing astrodynamics. Whenever one or more sensors view a target, scientific value is gained by the observation. This value is specified quantitatively as:

u_{ij} = value from satellite/sensor i observing target j

$w_{i_1 i_2 j}$ = additional value from satellites/sensors i_1 and i_2 observing target j simultaneously

Decision Variables

In time period t, the decision variables are:

$$x_{ij}^t = \begin{cases} 1 \text{ if satellite/sensor } i \text{ observes target } j \\ 0 \text{ otherwise} \end{cases}$$

$$y_{i_1 i_2 j}^t = \begin{cases} 1 \text{ if satellites/sensors } i_1 \text{ and } i_2 \text{ observe target } j \text{ simultaneously} \\ 0 \text{ otherwise} \end{cases}$$

Static Data

Static data is used to specify the data storage capabilities of the satellites. This data is static in the sense that it is particular to a sensor/satellite only and does not depend on any targets or their visibility status. There is an assumption that ground resources are sufficient for any number of the satellites to be downloading simultaneously. Thus each satellite picks the ground station with which it has the maximum transfer rate.

K_i = total capacity of satellite i (# of observation units that can be stored)

k_i^t = capacity on satellite i at the start of time period t

a_{EO} = data units per observation consumed by an EO sensor

a_{IR} = data units per observation consumed by an IR sensor

a_{SAR} = data units per observation consumed by an SAR sensor

d_i^t = maximum number of data units during t ime period t that can be downloaded from satellite i when a ground station is visible

The values of k_i^t can then be defined recursively as:

$$k^t{}_i = \begin{cases} k^{t-1}{}_i - \left(\sum_{i \in I_{EO,j}} x^{t-1}{}_{ij} a_{EO} + \sum_{i \in I_{IR,j}} x^{t-1}{}_{ij} a_{IR} + \sum_{i \in I_{SAR,j}} x^{t-1}{}_{ij} a_{SAR} \right) + d^{t-1}{}_i & \text{if } \sum_{g=1 \, to \, L} q^{t-1}{}_{ig} > 0 \\ k^{t-1}{}_i - \left(\sum_{i \in I_{EO,j}} x^{t-1}{}_{ij} a_{EO} + \sum_{i \in I_{IR,j}} x^{t-1}{}_{ij} a_{IR} + \sum_{i \in I_{SAR,j}} x^{t-1}{}_{ij} a_{SAR} \right) & \text{if } \sum_{g=1 \, to \, L} q^{t-1}{}_{ig} = 0 \end{cases}$$

Formulation

Given the data definitions specified above, the mathematical programming formulation is as follows for each time period t.

$$\max \sum_j \left(\begin{array}{l} \sum_{i=1 \text{ to } N} x^t{}_{ij} u_{ij} o_{ij}^t + \sum_{i_1 \in S_{EO}, i_2 \in S_{IR}} y^t{}_{i_1,i_2,j} w_{i_1,i_2,j} o_{i_1}^t o_{i_2}^t + \\ \sum_{i_1 \in S_{EO}, i_2 \in S_{SAR}} y^t{}_{i_1,i_2,j} w_{i_1,i_2,j} o_{i_1}^t o_{i_2}^t + \sum_{i_1 \in S_{SAR}, i_2 \in S_{IR}} y^t{}_{i_1,i_2,j} w_{i_1,i_2,j} o_{i_1}^t o_{i_2}^t \end{array} \right)$$

subject to

$$\begin{array}{ll}
\sum_{j=1..M} x_{ij}^t \le k_i^t & \text{for } i = 1 \text{ to } N \\
\sum_{j=1 \text{ to } M} x^t{}_{ij} \le 1 & \text{for } i = 1 \text{ to } N \\
\sum_{i \in S_{EO}} x^t{}_{ij} \le 1 & \text{for } j = 1 \text{ to } M \\
\sum_{i \in S_{IR}} x^t{}_{ij} \le 1 & \text{for } j = 1 \text{ to } M \\
\sum_{i \in S_{SAR}} x^t{}_{ij} \le 1 & \text{for } j = 1 \text{ to } M \\
\sum_{i=1 \text{ to } N} x_{ij}^t \le 2 & \text{for } j = 1 \text{ to } M \\
x^t{}_{i_1 j} + x^t{}_{i_2 j} - 2y^t{}_{i_1,i_2,j} \ge 0 & \text{for } i_1 \ne i_2, j = 1 \text{ to } M \\
x^t{}_{i_1 j} + x^t{}_{i_2 j} - 2y^t{}_{i_1,i_2,j} \le 1 & \text{for } i_1 \ne i_2, j = 1 \text{ to } M \\
x^t{}_{ij} \in \{0,1\} & \text{for } i = 1 \text{ to } N, j = 1 \text{ to } M \\
y^t{}_{i_1,i_2,j} \in \{0,1\} & \text{for } i = 1 \text{ to } N, j = 1 \text{ to } M
\end{array}$$

The output of the top-level optimization is at each time t and for each sensor the primary target it is tasked to look at and whether the satellite downloads observation data or not.

D. *BOTTOM LEVEL OPTIMIZATION*

The assignments of targets to sensors at each time period are input to the bottom level optimization. The output is a pointing command for each sensor for each time period. The sensors are modeled as being mounted on platform with two orthogonal gimbals. These gimbals are referred to as the x and y gimbal angles.

Data

To begin the definition of the data required for this optimizer, first define the following sets:

R = the set of targets

T = the time horizon for the problem

The model of the sensor includes constraints on the movement of each of the gimbals. These constraints include both bounds on the gimbal angles and slew rate constraints. The following data is defined for each $t = 1..T$.

$B(t)$	=	$\{r \in R \mid r$ is assigned to the sensor at time t$\}$
$A_r(t).[lu][xy]$	=	required bounds on the gimball angles for the sensor to be able to see target $r \in B(t)$ at time t (e.g., $A_r(t).ux$ is upper bound on x direction)
$P.[lu][xy]$	=	gimbal angle limits for the sensor in each direction (rad)
$S.[xy]$	=	slew rate limits for the sensor in each direction (rad Δt)

The notation *[xy]* is used to represent combinations of the specified variables. For example, *S.[xy]* indicates that both variables *S.x* and *S.y* are defined.

Decision Variables

The primary decision variables are:

$p(t).[xy]$ = gimbal angle for the sensor at time t for each direction

$$w_r(t) = \begin{cases} 1 & \text{if the sensor can see target } r \in B(t) \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

The variables are defined for all $t = 1..T$ and the values of *p(0).[xy]* are specified as input. The $w_r(t)$ variables are obviously a function of the $p(t)$ variables. Specifically, $w_r(t) = 1$ if and only if the following are true:

$$A_r(t).lx \le p(t).x \le A_r(t).ux$$
$$A_r(t).ly \le p(t).y \le A_r(t).uy$$

In support of this, define the following binary variables:

$$b_r(t).lx = \begin{cases} 1 \text{ if } A_r(t).lx \le p(t).x \\ 0 \text{ otherwise} \end{cases} \quad b_r(t).ux = \begin{cases} 1 \text{ if } p(t).x \le A_r(t).ux \\ 0 \text{ otherwise} \end{cases}$$

$$b_r(t).ly = \begin{cases} 1 \text{ if } A_r(t).ly \le p(t).y \\ 0 \text{ otherwise} \end{cases} \quad b_r(t).uy = \begin{cases} 1 \text{ if } p(t).y \le A_r(t).uy \\ 0 \text{ otherwise} \end{cases}$$

The relationship between $w_r(t)$ and $b_r(t)$ is then

$$4w_{vr}(t) \le b_{vr}(t).lx + b_{vr}(t).ux + b_{vr}(t).ly + b_{vr}(t).uy$$

The $b_r(t)$ variables are set with the following constraints

$$p(t).x \ge A_r(t).lx - M(1 - b_r(t).lx)$$
$$p(t).x \le A_r(t).ux + M(1 - b_r(t).ux)$$
$$p(t).y \ge A_r(t).ly - M(1 - b_r(t).ly)$$
$$p(t).y \le A_r(t).uy + M(1 - b_r(t).uy)$$

where M is a larger than the absolute value of any $A_r(t)$ entry.

Constraints

The pointing limits for the sensor are specified simply as:

$$P.lx \le p(t).x \le P.ux \qquad \forall t = 1..T$$
$$P.ly \le p(t).y \le P.uy \qquad \forall t = 1..T$$

The slew rates are specified as:

$$|p(t).x - p(t-1).x| \le S.x \qquad \forall t = 1..T$$
$$|p(t).y - p(t-1).y| \le S.y \qquad \forall t = 1..T$$

Objective Function

The objective function maximizes the value gained from achieving all of the assignments. This is calculated by multiplying the $w_r(t)$ variables by $V_r(t)$.

The null position of the sensor is pointing at the long-term targets, unless there is value to be gained from an ephemeral target[2], the sensor should try to point in the null position. To address this, a cost will be attributed to moving the sensor from the null position. Specifically, a term will be added to the objective function to minimize the absolute value of the $p(t).[xy]$ variables. Define the non-negative variables $D^{[+-]}(t).[xy]$ as:

$$D^+(t).x - D^-(t).x = p(t).x$$
$$D^+(t).y - D^-(t).y = p(t).y$$

The objective function will include a term to minimize

$$\sum_{t=1}^{T} \left(D^+(t).x + D^-(t).x + D^+(t).y + D^-(t).y \right)$$

[2] The value gained from an observation of an ephemeral target is assumed to be greater than the value gained from observing a long-term target.

Formulation

Given the data definitions specified above, the mathematical programming formulation is as follows.

$$\max \sum_{t=1}^{T} \left[\sum_{r \in B_v(t)} V_r(t) w_{vr}(t) - \gamma \left(D^+(t).x + D^-(t).x + D^+(t).y + D^-(t).y \right) \right]$$

Subject to

$$\begin{aligned} p(t).x - p(t-1).x &\le S.x & \forall t = 1..T \\ p(t).x - p(t-1).x &\ge -S.x & \forall t = 1..T \\ p(t).y - p(t-1).y &\le S.y & \forall t = 1..T \\ p(t).y - p(t-1).y &\ge -S.y & \forall t = 1..T \end{aligned}$$

$$\begin{aligned} p(t).x - Mb_r(t).lx &\ge A_r(t).lx - M & \forall r \in B_v(t), t = 1..T \\ p(t).x + Mb_r(t).ux &\le A_r(t).ux + M & \forall r \in B_v(t), t = 1..T \\ p(t).y - Mb_r(t).ly &\ge A_r(t).ly - M & \forall r \in B_v(t), t = 1..T \\ p(t).y + Mb_r(t).uy &\le A_r(t).uy + M & \forall r \in B_v(t), t = 1..T \end{aligned}$$

$$4w_r(t) - b_r(t).lx - b_r(t).ux - b_r(t).ly - b_r(t).uy \le 0 \qquad \forall r \in B_v(t), t = 1..T$$

$$\begin{aligned} D^+(t).x - D^-(t).x - p(t).x &= 0 & \forall t = 1..T \\ D^+(t).y - D^-(t).y - p(t).y &= 0 & \forall t = 1..T \end{aligned}$$

$$\begin{aligned} p(t).x &\in [P.lx, P.ux] \\ p(t).y &\in [P.ly, P.uy] \\ D^{[+-]}(t).[xy] &\in \Re \\ w_r(t) &\in \{0,1\} \\ b_r(t).[lu][xy] &\in \{0,1\} \end{aligned}$$

IV. FUTURE WORK

The development of the EPOS system has progressed so that both maneuvering and coasting satellites can be optimized to achieve optimal target viewing. A limitation of the current system is that maneuvering satellites treat their sensors as having a fixed attitude while coasting satellites utilize an autonomous sensor optimization level. The next version of EPOS, currently being developed, will merge these two approaches. Specifically, both maneuvering and coasting satellites will be addressed and all satellites will optimize the pointing of each sensor. In effect, the current version of EPOS and the capabilities of the previous version [1] will be merged into a single approach.

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